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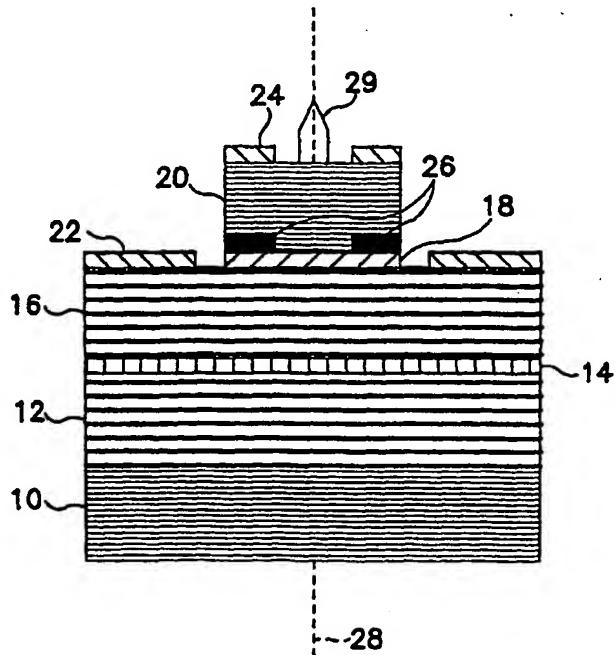
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(54) Title: INTRA-CAVITY OPTICALLY PUMPED VERTICAL CAVITY SURFACE EMITTING LASER

(57) Abstract

A semiconductor device includes a long-wavelength VCSEL integrated with a short-wavelength VCSEL where the long-wavelength active medium is located between the mirrors of the short-wavelength VCSEL. The short-wavelength VCSEL optically pumps the long-wavelength VCSEL to emit long-wavelength laser light.



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**INTRA-CAVITY OPTICALLY PUMPED
VERTICAL CAVITY SURFACE EMITTING LASER**

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BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to semiconductor devices that include a long-wavelength vertical cavity surface emitting laser (VCSEL) optically pumped by a short-wavelength VCSEL.

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2. Description of the Related Art

A vertical cavity surface emitting laser (VCSEL) is a semiconductor laser including a semiconductor layer of optically active material, such as gallium arsenide or indium phosphide. The optically active material is sandwiched between mirrors formed of highly-reflective layers of metallic material, dielectric material, or epitaxially-grown semiconductor material. Conventionally, one of the mirrors is partially reflective so as to pass a portion of the coherent light which builds up in a resonating cavity formed by the mirrors sandwiching the active layer.

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Lasing structures require optical confinement in the resonating cavity and carrier confinement in the active region to achieve efficient conversion of pumping electrons into stimulated photons through population inversion. The standing wave of reflected optical energy in the resonating cavity has a characteristic cross-section giving rise to an optical mode. A desirable optical mode is the single fundamental transverse mode, for example, the HE₁₁ mode of a cylindrical waveguide. A single mode signal from a VCSEL is easily coupled into an optical fiber, has low divergence, and is inherently single frequency in operation.

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In order to reach the threshold for lasing, the total gain of a VCSEL must equal the total loss of the VCSEL. Unfortunately, due to the compact nature of

VCSELs, the amount of gain media is limited. For efficient VCSELs, at least one of the two required mirrors must have a reflectivity greater than approximately 99.5%. It is more difficult to meet this requirement in long-wavelength VCSELs than in short-wavelength VCSELs because such high 5 reflectivity mirrors are difficult to grow in the same epitaxial step as the long-wavelength active region. Because epitaxially-grown mirrors often do not enable sufficiently high reflectivity, some VCSELs are formed by wafer fusing the top and bottom mirrors to the active region.

Wafer fusion is a process by which materials of different lattice constant 10 are atomically joined by applying pressure and heat to create a real physical bond. Thus, wafer fusion of one or both of the mirrors to the active region is used to increase the reflectivity provided by either or both of the mirrors to compensate for the small amount of gain media so that the lasing threshold can be reached and maintained.

15 A long-wavelength VCSEL can be optically coupled to and optically pumped by a shorter wavelength, electrically pumped VCSEL. U.S. Patent No. 5,513,204 to Jayaraman entitled "LONG WAVELENGTH, VERTICAL CAVITY SURFACE EMITTING LASER WITH VERTICALLY INTEGRATED OPTICAL PUMP" describes an example of a short-wavelength 20 VCSEL optically pumping a long-wavelength VCSEL.

SUMMARY OF THE INVENTION

According to an exemplary embodiment of the invention, an integrated 25 semiconductor device includes a long-wavelength vertical cavity surface emitting laser (VCSEL) optically pumped by a short-wavelength VCSEL. The long-wavelength active medium is interposed between the mirrors of the short-wavelength VCSEL. The short-wavelength VCSEL optically pumps the long-wavelength VCSEL to emit long-wavelength laser light.

Other features and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawing, which illustrate, by way of example, the features of the invention.

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BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 illustrates a first embodiment of a semiconductor device in accordance with the principles of the invention;

10 FIG. 2 illustrates a second embodiment of a semiconductor device in accordance with the principles of the invention;

FIG. 3 illustrates a third embodiment of a semiconductor device in accordance with the principles of the invention;

15 FIG. 4 illustrates a fourth embodiment of a semiconductor device in accordance with the principles of the invention;

FIG. 5 illustrates a fifth embodiment of a semiconductor device in accordance with the principles of the invention;

FIG. 6 illustrates a sixth embodiment of a semiconductor device in accordance with the principles of the invention; and

20 FIG. 7 illustrates a seventh embodiment of a semiconductor device in accordance with the principles of the invention.

DETAILED DESCRIPTION

In this description, "top" or "upper" are relative terms referring to regions 25 of the semiconductor device away from the substrate, and "bottom" and "lower" mean toward the substrate.

As shown in the drawings for purposes of illustration, a long-wavelength vertical cavity surface emitting laser (VCSEL) is optically pumped by a short-wavelength VCSEL in a monolithic integrated semiconductor device. The

VCSEL designed to emit laser light at a short wavelength (e.g., 980 nm) and the VCSEL designed to emit laser light at a long wavelength (e.g., 1310 nm) overlap spatially. Part of one VCSEL exists within part of the other VCSEL such that the active region producing the shorter wavelength laser light is more 5 efficiently optically coupled to the active region that produces the longer wavelength laser light. More specifically, the longer wavelength active region is located at least partially between the mirrors that define the shorter wavelength optical resonating cavity portion of the semiconductor device. As a result, it is possible to overdesign the mirrors such that virtually no shorter 10 wavelength emission is permitted to escape the shorter wavelength optical resonating cavity portion of the semiconductor device, and substantially all of the shorter wavelength emission is used to optically pump the longer wavelength active region. Semiconductor devices in accordance with the principles of the invention can be manufactured in groups or arrays in a wafer- 15 scale integrated circuit system.

High-performance VCSELs have been made using active regions made up of InGaAs. Such high-performance VCSELs operate to emit laser light in the short wavelength range of 830 nm to 1150 nm. The short wavelength light can be efficiently converted to 1310 nm light emitted from a semiconductor 20 device using the intra-cavity optical pumping system taught herein.

In a specific embodiment illustrated in FIG. 1, a monolithically integrated semiconductor device includes a plurality of stacked layers. A long-wavelength VCSEL and a short-wavelength optical pump VCSEL are integrated within the semiconductor device illustrated in FIG. 1.

25 Referring to FIG. 1, the semiconductor device includes an undoped bottom 980 nm mirror 10. An undoped bottom 1310 nm mirror 12 is disposed above the bottom 980 nm mirror 10. A 1310 nm active region 14 is disposed above the bottom 1310 nm mirror 12. A top 1310 nm mirror 16 is disposed above the 1310 nm active region 14. The 1310 nm mirror 16 is mostly undoped

except for the top of the mirror which is n-doped. A 980 nm active region 18 is disposed above the top 1310 nm mirror 16. A p-doped top 980 nm mirror 20 is disposed above the 980 nm active region 18. An annular bottom contact 22 is applied to the top 1310 nm mirror 16, circumscribing the 980 nm active region

5 18. An annular top contact 24 is applied to the top 980 nm mirror 20. An annular current confinement region 26 is disposed between the 980 nm active region 18 and the top 980 nm mirror 20. The top contact, the bottom contact and the current confinement region are centered around a central vertical axis
28. The current confinement region 26 can be produced by implantation, lateral
10 oxidation, or undercut etching.

The top and bottom contacts 24, 22 made on the top 980 nm mirror 20 and on the top 1310 nm mirror 16, respectively, are used to electrically pump the 980 nm active region 18. The annular current confinement region 26 near the 980 nm active region 18 provides current constriction, which defines the
15 lasing portion of the 980 nm active region 18.

Laser light having a wavelength of 980 nm is produced by driving current through the 980 nm active region 18. The 980 nm laser light resonates between the top 980 nm mirror 20 and the bottom 980 nm mirror 10. The 980 nm mirrors 20, 10 are designed to confine as much of the 980 nm emission as
20 possible. Therefore, the 980 nm emission is substantially confined within the 980 nm optical resonating cavity rather than emitted from the optical resonating cavity, and therefore more efficiently optically pumps the 1310 nm active region 14 to produce 1310 nm laser light.

The 1310 nm laser light resonates between the top 1310 nm mirror 16 and the bottom 1310 nm mirror 12. The bottom 1310 nm mirror 12 and the majority of the top 1310 nm mirror 16 are undoped to reduce optical loss at the 1310 nm wavelength and increase the device performance. The top 1310 nm mirror 16 is doped, for good conduction of electrical current, in the top several mirror periods where needed for current conduction. Optionally, optical

confinement can be used in the 1310 nm optical resonating cavity to further increase device performance. Laser light 29 having a wavelength of 1310 nm is emitted upward from the top 980 nm mirror 20. The semiconductor device can also be designed such that laser light is emitted down through the bottom 980 5 nm mirror 10.

In another specific embodiment illustrated in FIG. 2, a partial 980 nm mirror is inserted between a 980 nm active region and a top 1310 nm mirror.

Referring to FIG. 2, an undoped bottom 1310 nm mirror 30 is disposed above an undoped bottom 980 nm mirror 32. A 1310 nm active region 34 is 10 disposed above the bottom 1310 nm mirror 30. An undoped top 1310 nm mirror 36 is disposed above the 1310 nm active region 34. The top 1310 nm mirror 36 is undoped to minimize optical loss in the 1310 nm resonating cavity.

An n-doped partial 980 nm mirror 38 is disposed above the top 1310 nm mirror 36. The partial 980 nm mirror 38 conducts current.

15 A 980 nm active region 40 is disposed above the partial 980 nm mirror 38. A p-doped top 980 nm mirror 42 is disposed above the 980 nm active region 40.

An annular bottom contact 44 is applied to the partial 980 nm mirror 38, circumscribing the 980 nm active region 40. An annular top contact 46 is 20 applied to the top 980 nm mirror 42. An annular current confinement region 48 is disposed between the 980 nm active region 40 and the top 980 nm mirror 42. The top contact, the bottom contact and the current confinement region are centered around a central vertical axis 50. The annular current confinement region 48 can be produced by implantation, lateral oxidation, or undercut 25 etching.

The top and bottom contacts 46, 44 made on the top 980 nm mirror 42 and the partial 980 nm mirror 38, respectively, are used to electrically pump the 980 nm active region 40. The annular current confinement region 48 near the 980 nm active region 40 provides current constriction, which defines the lasing

portion of the 980 nm active region 40. Driving current through the 980 nm active region 40 produces 980 nm laser light. The partial 980 nm mirror 38 decreases the round trip absorption loss of 980 nm laser light in the 1310 nm active region 34. The 980 nm partial mirror 38 allows less of the 980 nm light 5 to circulate through the 1310 nm cavity, thus allowing less to be absorbed.

The goal is for the total round trip loss of the 980 nm light in the semiconductor device illustrated in FIG. 2 to be equivalent to a typical high performance 850 nm or 980 nm vertical cavity laser. The loss is caused by the 980 nm light being absorbed in the long-wavelength cavity rather than the 980 10 nm laser light escaping from the short-wavelength cavity.

Laser light 51 having a wavelength of 1310 nm is emitted up from the top 980 nm mirror 42. Alternatively, the semiconductor device can be designed such that laser light is emitted from the bottom 980 nm mirror 32.

In another specific embodiment illustrated in FIG. 3, a spacer layer is 15 used between a 980 nm active region and a 1310 nm active region. Referring to FIG. 3, the semiconductor device includes a plurality of layers, in which an undoped bottom 1310 nm mirror 52 is disposed above an undoped bottom 980 nm mirror 54. A 1310 nm active region 56 is disposed above the bottom 1310 nm mirror 52. An undoped top 1310 nm mirror 58 is disposed above the 1310 20 nm active region 56. A thermal spacer layer 60 is disposed above the top 1310 nm mirror 58. The material composition of the spacer layer 60 depends on whether a high thermal conductivity material or a low thermal conductivity material is desired. If a high thermal conductivity material is desired, the spacer layer can, for example, be made of GaAs. If a low thermal conductivity 25 material is desired, then the spacer layer can, for example, be made of AlGaAs.

An n-doped partial 980 nm mirror 62 is disposed above the thermal spacer layer 60. A 980 nm active region 64 is disposed above the partial 980 nm mirror 62. A p-doped top 980 nm mirror 66 is disposed above the 980 nm active region 64. An annular bottom contact 68 is disposed above the partial

980 nm mirror 62, circumscribing the 980 nm active region 64. An annular top contact 70 is disposed above the top 980 nm mirror 66. A current confinement region 72 is disposed between the 980 nm active region 64 and the top 980 nm mirror 66. The top contact, the bottom contact and the current confinement region are centered about a central vertical axis 74. The current confinement region 72 can be produced by implantation, lateral oxidation, or undercut etching.

10 The top and bottom contacts 70, 68 made on the top 980 nm mirror 66 and on the partial 980 nm mirror 62, respectively, are used to electrically pump the 980 nm active region 64. The annular current confinement region 72 funnels current through a portion of the 980 nm active region 64.

15 Driving current through the 980 nm active region 64 causes the 980 nm active region 64 to emit 980 nm laser light. The 980 nm laser light resonates between the top 980 nm mirror 66 and the bottom 980 nm mirror 54. The 980 nm mirrors 66, 54 are designed to confine as much of the 980 nm laser light as possible. As a result, the 980 nm emission is substantially confined within the 980 nm optical resonating cavity, and therefore more efficiently optically pumps the 1310 nm active region 56 to produce 1310 nm laser light.

20 The 1310 nm laser light resonates between the top 1310 nm mirror 58 and the bottom 1310 nm mirror 52. The bottom 1310 nm mirror 52 and all of the top 1310 nm mirror 58 are undoped to reduce optical loss at the 1310 nm wavelength and increase device performance.

25 The spacer layer 60 increases the vertical dimension of the 980 nm optical resonating cavity and also decreases the thermal crosstalk between the 980 nm active region 64 and the 1310 nm active region 56. The thermal spacer layer 60 is preferably undoped to reduce optical losses and can be made of a high thermal conductivity material to maximize device performance.

Laser light 75 having a wavelength of 1310 nm is emitted from the semiconductor through the top 980 nm mirror 66. Alternatively, the

semiconductor device can be designed to emit laser light down through the bottom mirror 54.

In another specific embodiment illustrated in FIG. 4, a monolithically integrated semiconductor device includes a plurality of layers of 5 semiconductor. The plurality of layers includes a 980 nm active region 76 disposed above an n-doped bottom 980 nm mirror 78. A p-doped partial 980 nm mirror 80 is disposed above the 980 nm active region 76. An undoped bottom 1310 nm mirror 82 is disposed above the partial 980 nm mirror 80. A 1310 nm active region 84 is disposed above the bottom 1310 nm mirror 82. An 10 undoped top 1310 nm mirror 86 is disposed above the 1310 nm active region 84. An undoped top 980 nm mirror 88 is disposed above the top 1310 nm mirror 86.

An annular bottom contact 90 is applied to the bottom 980 nm mirror 78, circumscribing the 980 nm active region 76. An annular top contact 92 is 15 applied to the partial 980 nm mirror 80, circumscribing the bottom 1310 nm mirror 82. An annular current confinement region 94 is disposed between the 980 nm active region 76 and the partial 980 nm mirror 80. The top contact, the bottom contact and the current confinement region are centered around a central vertical axis 96.

20 The top and bottom contacts 92, 90 are used to electrically pump the 980 nm active region 76. The annular current confinement region 94 funnels current through a portion of the 980 nm active region 76 that corresponds to the single fundamental transverse mode.

Driving current through the 980 nm active region 76 causes the 980 nm 25 active region 76 to emit 980 nm laser light. The 980 nm laser light resonates between the top 980 nm mirror 88 and the bottom 980 nm mirror 78. The 980 nm emission is largely confined within the 980 nm cavity rather than emitted from the cavity, and efficiently pumps the 1310 nm active region 84 to produce 1310 nm laser light. The 1310 nm light resonates between the top 1310 nm

mirror 86 and the bottom 1310 nm mirror 82. The bottom 1310 nm mirror 82 and the majority of the top 1310 nm mirror 86 are undoped to reduce optical loss at the 1310 nm wavelength. Laser light 98 having a wavelength of 1310 nm can be emitted upward from the top 980 nm mirror 88. Alternatively, the 5 semiconductor device can be arranged such that laser light is emitted downward from the bottom 980 nm mirror 78.

In another specific embodiment of the semiconductor device illustrated in FIG. 5, a dual-wavelength mirror is used in replacement of the top 980 nm mirror and the top 1310 nm mirror that are depicted in FIG. 4. Referring to 10 FIG. 5, a 980 nm active region 102 is disposed above an n-doped 980 nm mirror 104. A p-doped partial 980 nm mirror 106 is disposed above the 980 nm active region 102. An undoped 1310 nm mirror 108 is disposed above the partial 980 nm mirror 106. A 1310 nm active region 110 is disposed above the 1310 nm mirror 108. An undoped dual-wavelength 980 nm/1310 nm mirror 112 is disposed above the 1310 nm active region 110. The reflectivity of a 980 15 nm mirror and the reflectivity of a 1310 nm mirror are combined in the dual-wavelength mirror 112.

An annular bottom contact 114 is applied to the 980 nm mirror 104, circumscribing the 980 nm active region 102. An annular top contact 116 is 20 applied to the partial 980 nm mirror 106, circumscribing the 1310 nm mirror 108. An annular current confinement region 118 is disposed between the 980 nm active region 102 and the partial 980 nm mirror 106 to constrict current to flow through a portion of the active region. The top contact, the bottom contact and the current confinement region are centered around a central vertical axis 25 119.

The dual-wavelength mirror 112 is designed to reflect strongly at 980 nm and less strongly at 1310 nm so as to allow some of the 1310 nm laser emission to escape. The dual-wavelength mirror can be embodied as, for example, a distributed Bragg reflector (DBR) with a large refractive index

difference, where dielectric materials are used to obtain the large refractive index difference. Examples of the dielectric materials that can be used in the dual-wavelength mirror 112 include: CaF, SiO₂, TiO₂, ZnO, and Nb₂O₅. The dual-wavelength mirror can also be made using the technique described in the 5 paper entitled, "Dual mirror and resonant cavity operating at 1.3 and 1.55 μ m," Electron. Lett. Vol. 30 (8), pages 643-645 (1994) by S. S. Murtaza, A. Srinivasan, Y. C. Shih, J. C. Campbell and B. G. Streetman, using materials with a lower index contrast. This technique allows the two wavelengths to be spaced further apart. For example, a dual 980 nm/1310 nm mirror can be 10 formed using GaAs and high-aluminum AlGaAs.

Driving current through the 980 nm active region 102 causes the 980 nm active region 102 to emit laser light having a wavelength of 980 nm. The 980 nm laser light resonates between the dual-wavelength mirror 112 and the 980 nm mirror 104. The 980 nm emission is substantially confined between the 15 dual-wavelength mirror 112 and the 980 nm mirror 104 and efficiently optically pumps the 1310 nm active region 110 to produce 1310 nm laser light. Because the dual-wavelength mirror 112 is partially transmissive to 1310 nm light, the 1310 nm laser light resonates between the dual-wavelength mirror 112 and the 1310 nm mirror 108 with some 1310 nm laser light 121 being emitted upward 20 from the dual-wavelength mirror 112.

In an alternate configuration, laser light can be emitted downward from the 980 nm mirror 104.

Dual-wavelength mirrors can also be used at the bottom of a monolithically integrated semiconductor device in accordance with the 25 principles of the invention, or at both the bottom and the top of a monolithically integrated semiconductor device, as illustrated in FIG. 6. Referring to FIG. 6, an n-doped bottom partial 980 nm mirror 120 is disposed above an undoped bottom dual-wavelength 980 nm/1310 nm mirror 122. The reflectivity of a 980 nm mirror and the reflectivity of a 1310 nm mirror are provided by the bottom

dual-wavelength mirror 122. A 980 nm active region 124 is disposed above the bottom partial 980 nm mirror 120. A p-doped top partial 980 nm mirror 126 is disposed above the 980 nm active region 124. A 1310 nm active region 128 is disposed above the top partial 980 nm mirror 126. An undoped top dual-wavelength 980 nm/1310 nm mirror 130 is disposed above the 1310 nm active region 128.

An annular bottom contact 132 is applied to the bottom partial 980 nm mirror 120, circumscribing the 980 nm active region 124. An annular top contact 134 is applied to the top partial 980 nm mirror 126, circumscribing the 1310 nm active region 128. An annular current confinement region 136 is disposed between the 980 nm active region 124 and the top partial 980 nm mirror 126. The top contact, the bottom contact and the current confinement region are centered with respect to a central vertical axis 138.

The top and bottom contacts 134, 132 made on the top partial 980 nm mirror 126 and on the bottom partial 980 nm mirror 120, respectively, are used to electrically pump the 980 nm active region 124. The annular current confinement region 136 funnels current through a portion of the 980 nm active region 124, which defines the lasing portion of the 980 nm active region 124.

Driving current through the 980 nm active region 124 causes the 980 nm active region 124 to emit 980 nm laser light. The 980 nm laser light resonates between the top dual-wavelength mirror 130 and the bottom dual-wavelength mirror 122. The 980 nm light optically pumps the 1310 nm active region 128 to produce 1310 nm laser light. The 1310 nm laser light resonates between the top dual-wavelength mirror 130 and the bottom dual-wavelength mirror 122. Laser light 140 having a wavelength of 1310 nm is emitted upward from the dual-wavelength mirror 130. The semiconductor device can also be designed such that laser light is emitted downward from dual-wavelength mirror 122.

By way of example and not limitation, the bottom dual-wavelength mirror 122 and the top dual-wavelength mirror 130 are reflective to 980 nm and

1310 nm wavelengths. The electrically pumped portion of the semiconductor device preferably ought to be at a shorter wavelength than the optically pumped portion of the device. Any pair of wavelengths that meet this criterion can be used. For example, 850 nm can be used for the short-wavelength electrically 5 pumped cavity and 1550 nm can be used for the long-wavelength optically pumped cavity.

With respect to FIG. 7, another embodiment of the semiconductor device includes a partial short-wavelength mirror inserted between the short-wavelength active region and the top long-wavelength mirror. Referring to 10 FIG. 7, a 1310 nm active region 146 is disposed above a dual-wavelength mirror 148. The dual-wavelength mirror 148 is reflective to 980 nm light and to 1310 nm light. A 1310 nm mirror 150 is disposed above the 1310 nm active region 146. A thermal spacer layer 152 is disposed above the 1310 nm mirror 150. A partial 980 nm mirror 154 is disposed above the thermal spacer layer 152. A 980 nm active region 156 is disposed above the partial 980 nm mirror 154. A 980 nm mirror 158 is disposed above the 980 nm active region 156. A bottom contact 160 is disposed above the partial 980 nm mirror 154, circumscribing the 980 nm active region 156 and centered about a central vertical axis 162. A top contact 164 is disposed above the 980 nm mirror 158, 15 centered about the central vertical axis 162. A current confinement region 166 is disposed between the 980 nm mirror 158 and the 980 nm active region 156.

The partial 980 nm mirror 154 conducts current while the 1310 nm mirror 150 is undoped to minimize optical loss in the 1310 nm cavity. The partial 980 nm mirror 154 is used to maximize the performance of the structure 25 by adjusting the round trip absorption loss of the 1310 nm active region 146 for the 1310 nm emission. The ideal is for the total round trip loss to be equivalent to a typical high performance 850 nm vertical cavity laser. Instead of the loss coming from lasing light escaping from the cavity, loss comes from light being absorbed in the long wavelength cavity. The spacer layer 152 is added both for

small phase adjustments to the 980 nm optical field and to provide some thermal isolation between the two active regions. The dual-wavelength mirror 148 is reflective to 980 nm light and 1310 nm light and is made using the AlGaAs material system as described in the paper entitled, "Dual mirror and resonant cavity operating at 1.3 and 1.55 μ m," Electron. Lett. Vol. 30 (8), pages 643-645 (1994) by S. S. Murtaza, A. Srinivasan, Y. C. Shih, J. C. Campbell and B. G. Streetman, using materials with a lower index contrast. Laser light 168 having a wavelength of 1310 nm is emitted upward from the 980 nm mirror 158. In an alternate configuration, the semiconductor device can be designed 10 such that laser light is emitted downward from the dual-wavelength mirror 148.

The monolithically integrated multi-layer semiconductor device produced in accordance with the principles of the invention includes a long-wavelength VCSEL optically pumped by a short-wavelength VCSEL, where the long-wavelength active medium is located between the mirrors of the short-wavelength VCSEL. It is contemplated that arrays of semiconductor devices can 15 be produced on a wafer scale using the invention.

As should be understood, it is within the scope of the present invention to include an array of short-wavelength VCSELs within which a single, or an array of long-wavelength VCSELs are integrated. More particularly, a closely spaced 20 array of short-wavelength VCSELs can be used to optically pump a much larger long-wavelength VCSEL and in doing so, produce more long-wavelength radiation than may be possible using a single short-wavelength VCSEL.

While several particular forms of the invention have been illustrated and described, it will also be apparent that various modifications can be made 25 without departing from the spirit and scope of the invention.

WHAT IS CLAIMED IS:

- 1 1. A semiconductor device, comprising:
 - 2 a short-wavelength vertical cavity surface emitting laser (VCSEL)
 - 3 having top and bottom short-wavelength mirrors and a short-wavelength active
 - 4 medium disposed between the top and bottom short-wavelength mirrors, the
 - 5 short-wavelength active medium emitting laser light at a short wavelength; and
 - 6 a long-wavelength VCSEL having top and bottom long-wavelength
 - 7 mirrors and a long-wavelength active medium disposed between the top and
 - 8 bottom long-wavelength mirrors, the long-wavelength active medium emitting
 - 9 at a long wavelength;
- 10 wherein the long-wavelength active medium is at least partially
- 11 disposed within the short-wavelength VCSEL.
- 1 2. The semiconductor device of claim 1, wherein:
 - 2 the top short-wavelength mirror and the top long-wavelength
 - 3 mirror are embodied in a dual-wavelength mirror.
- 1 3. The semiconductor device of claim 1, wherein:
 - 2 the bottom short-wavelength mirror and the bottom long-wavelength
 - 3 mirror are embodied in a dual-wavelength mirror.
- 1 4. The semiconductor device of claim 1, wherein:
 - 2 the top short-wavelength mirror and the top long-wavelength mirror are
 - 3 embodied in a dual-wavelength mirror, and
 - 4 the bottom short-wavelength mirror and the bottom long-wavelength
 - 5 mirror are embodied in a dual-wavelength mirror.

1 5. A semiconductor device, comprising:
2 a short-wavelength vertical cavity surface emitting laser (VCSEL); and
3 a long-wavelength VCSEL optically pumped by the short-wavelength
4 VCSEL,
5 the long-wavelength VCSEL including a long-wavelength active
6 medium at least partially disposed within the short-wavelength VCSEL.

1 6. The semiconductor device of claim 5, further comprising:
2 a dual-wavelength mirror that is part of both the short-wavelength
3 VCSEL and the long-wavelength VCSEL.

1 7. An array of semiconductor devices, wherein each semiconductor
2 device is defined according to claim 1.

1 8. The semiconductor device of claim 5, wherein:
2 the long-wavelength VCSEL includes a dual-wavelength mirror and a
3 long-wavelength mirror, and
4 the short-wavelength VCSEL includes said dual-wavelength mirror and
5 a short-wavelength mirror.

1 9. The semiconductor device of claim 5, wherein:
2 the long-wavelength VCSEL includes two dual-wavelength mirrors, and
3 the short-wavelength VCSEL includes said two dual-wavelength mirrors.

1 10. A method of producing laser light from a semiconductor device,
2 comprising the steps of:

- 3 integrating a long-wavelength vertical cavity surface emitting laser
- 4 (VCSEL) and a short-wavelength VCSEL by disposing a long-wavelength
- 5 active medium at least partially within the short-wavelength VCSEL;
- 6 electrically pumping the short-wavelength VCSEL thereby optically
- 7 pumping the long-wavelength VCSEL; and
- 8 emitting long-wavelength laser light from the long-wavelength VCSEL.

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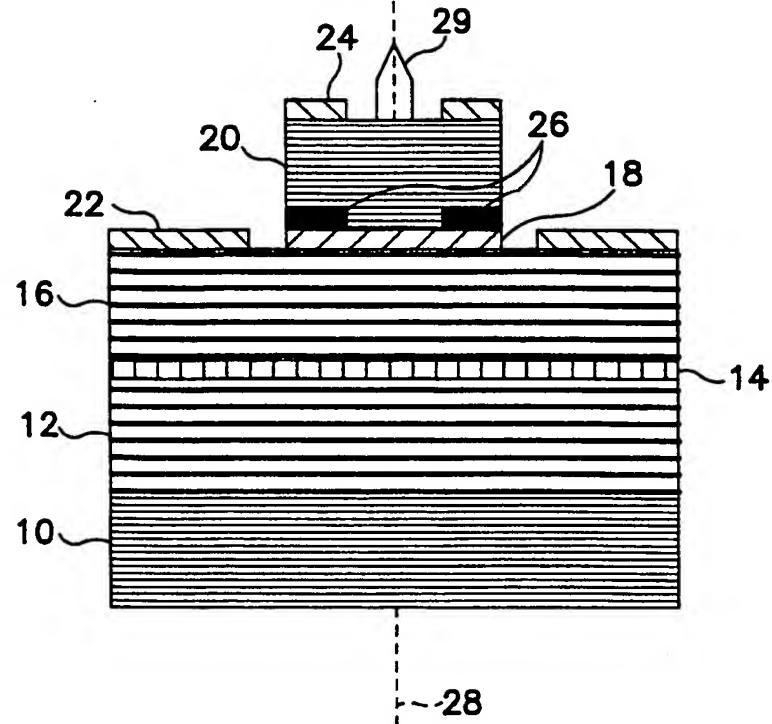


FIG. 1

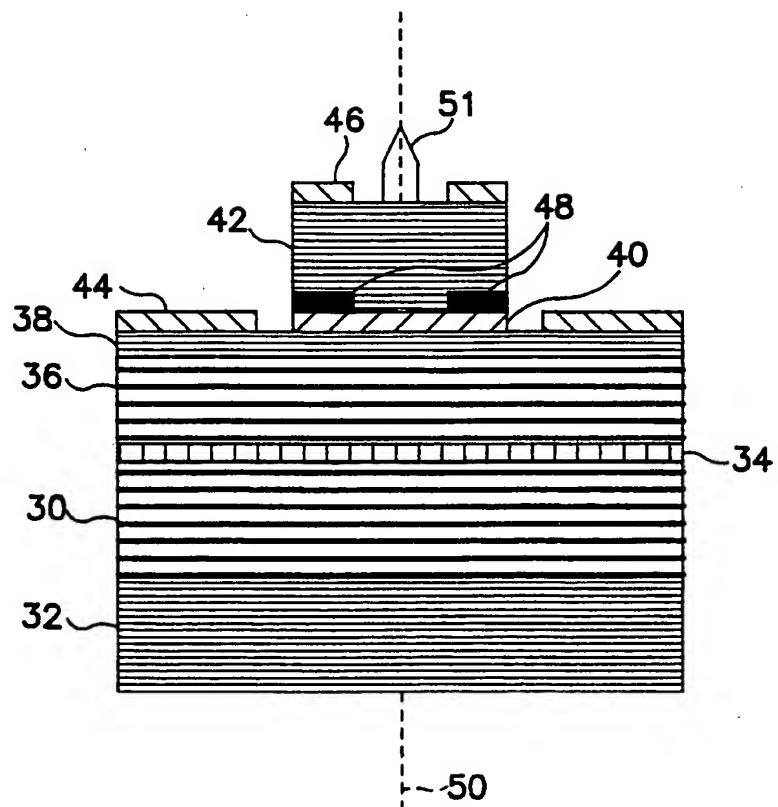
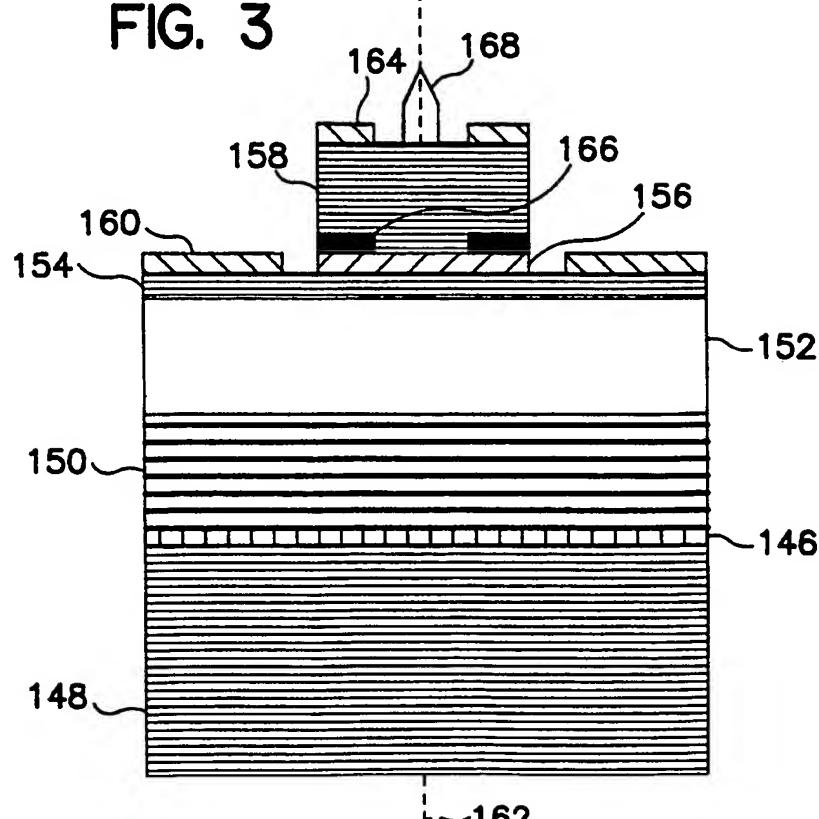
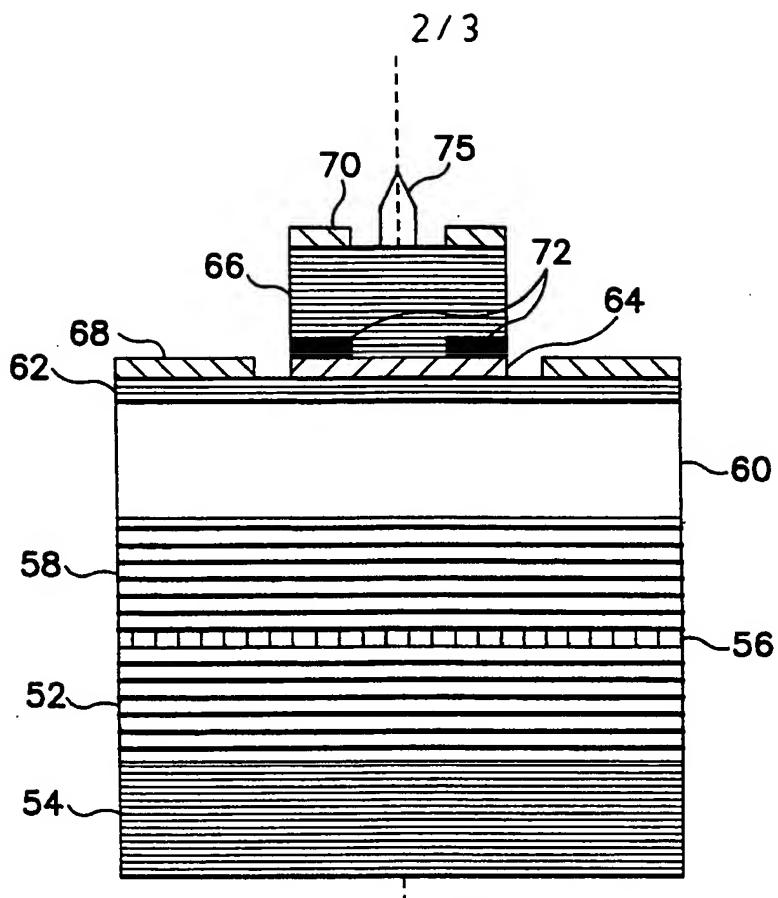


FIG. 2



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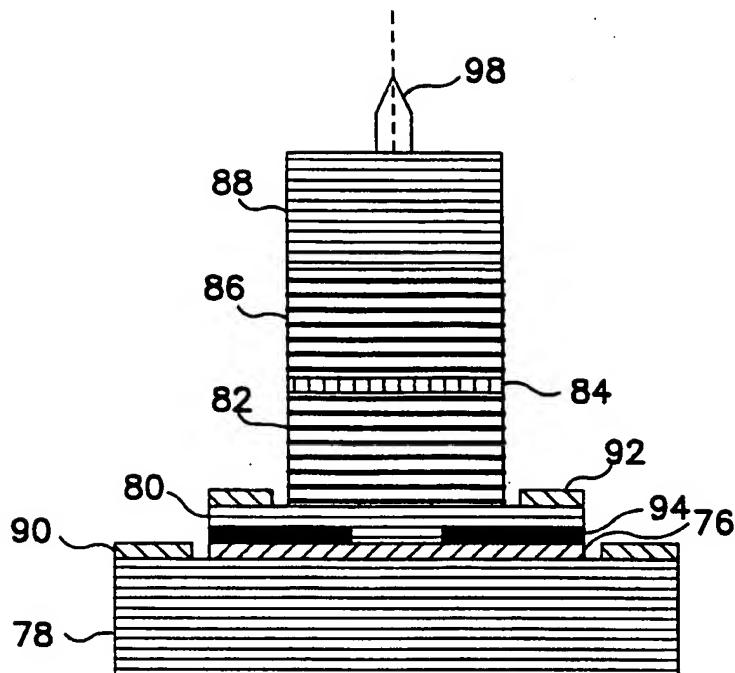


FIG. 4

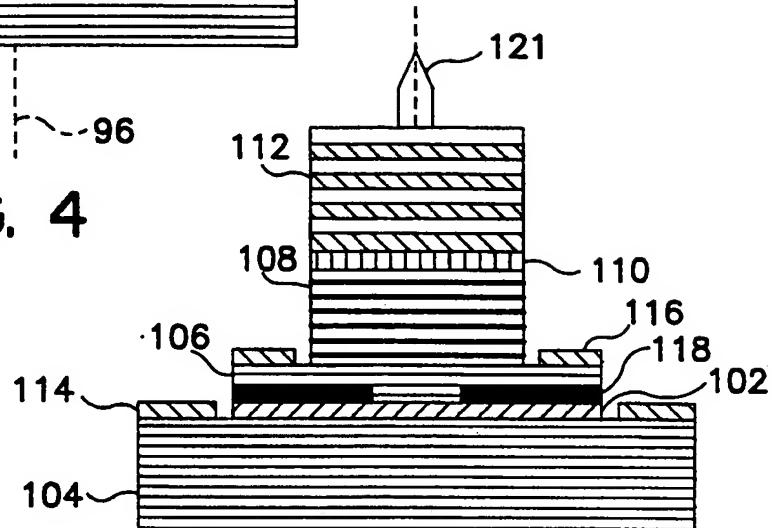


FIG. 5

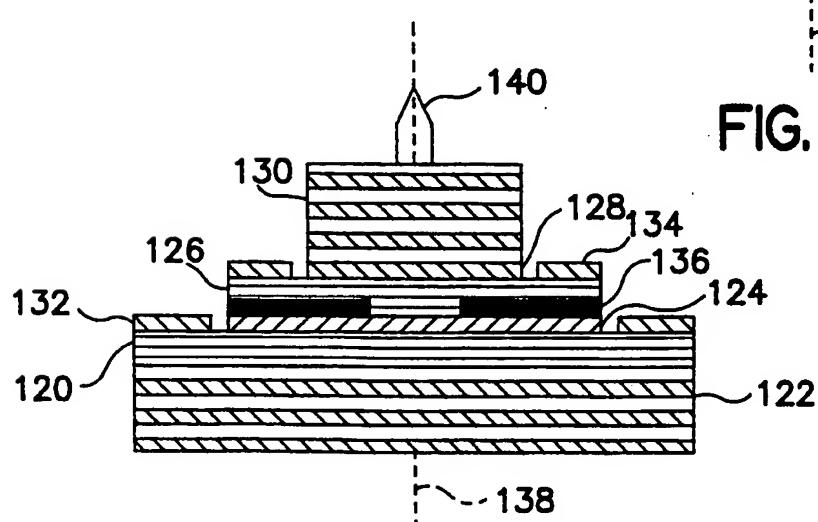


FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/09706

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S5/183

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|----------|--|-----------------------|
| X | US 5 754 578 A (JAYARAMAN VIJAYSEKHAR) 19 May 1998 (1998-05-19) column 5, line 13 - line 15; figure 4 ---- | 1,3,5,6, 8,10 |
| Y | US 5 513 204 A (JAYARAMAN VIJAYSEKHAR) 30 April 1996 (1996-04-30) cited in the application the whole document ---- | 1,5,10 |
| Y | US 5 796 771 A (DENBAARS STEVEN P ET AL) 18 August 1998 (1998-08-18) column 7, line 65 -column 8, line 34; figure 7 ---- | 1,5,10 |
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Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

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Date of the actual completion of the international search

26 July 2000

Date of mailing of the international search report

02/08/2000

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

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| Patent document cited in search report | Publication date | Patent family member(s) | | | Publication date |
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